

Effect of Substrate Permittivity and Thickness on Performance of Single-Layer, Wideband, U-Slot Antennas on Microwave Substrates

V. Natarajan and D. Chatterjee

Division of Computer Science and Electrical Engineering
570-F Flarsheim Hall, University of Missouri-Kansas City (UMKC),
5100 Rockhill Road, Kansas City, MO 64110, USA;
e-mail : chatd@umkc.edu

Abstract

This paper presents effects of substrate permittivity and thickness on the performance characteristics like impedance bandwidth, radiation efficiency and gain of a single-layer, wideband, U-slot antenna. The effects of variation on substrate thickness on these performance metrics are investigated via simulation using state-of-art, electromagnetic simulator IE3D. Results are presented for U-slot antenna topologies on low ($\epsilon_r = 2.2$), medium ($\epsilon_r = 4.5$) and high ($\epsilon_r = 9.8$) substrate permittivities on infinite grounded dielectrics.

I. INTRODUCTION

Recently, a single-layer, probe-fed, rectangular microstrip antenna with U-shaped slot etched on the surface of the radiating patch was shown to exhibit wideband impedance characteristics [1]. Since then, several designs of this "U-slot" antenna, on both foam [1] and microwave substrates [2] have been presented in the literature. However, an analytical model to explain the working of the U-slot antenna has not yet been presented. In the absence of an analytical model, two different empirical techniques to initiate the design of a U-slot microstrip antenna on microwave substrates, based on some specifications known *a priori*, have been presented in [3]-[5] and [6], respectively. In most cases, the initial U-slot antenna geometries obtained from these empirical methods must be further optimized via commercially available CAD tools, such as IE3D [7], to further enhance the wideband performance of the U-slot antenna. Therefore, additional information/criteria, which reduce the overall optimization cycles will prove invaluable to designers.

The purpose of this investigation is to study effects of substrate permittivity and thickness on the performance characteristics of U-slot antenna geometries on microwave substrates. Since, substrate permittivity and thickness are used as input to the empirical techniques in [5] and [6], a good selection of these parameters will yield superior performance and/or reduced optimization cycles. The scope of results presented in this investigation are restricted to U-slot antenna implementation on infinite, grounded dielectrics, and simulated via IE3D. Previous work in [8] analyzed the effects of substrate permittivity and thickness on impedance bandwidth, resonant resistance, directivity and radiation efficiency of a square patch microstrip antenna, using surface current model and appropriate Green's functions. The effects of variation of resonant frequencies on the above mentioned characteristics for a rectangular patch antenna on microwave substrates are also presented in [1, ch. 4, pp. 280-287]. However, in the absence of an analytical model for the U-slot antenna, this investigation uses CAD tool IE3D to study and document effects of substrate permittivity and thickness on the performance of U-slot antenna geometries. The organization of the paper is presented next.

The ensuing section presents the procedure used to study the effects of substrate permittivity and thickness on the performance of U-slot antennas. The results of the simulation study are presented and

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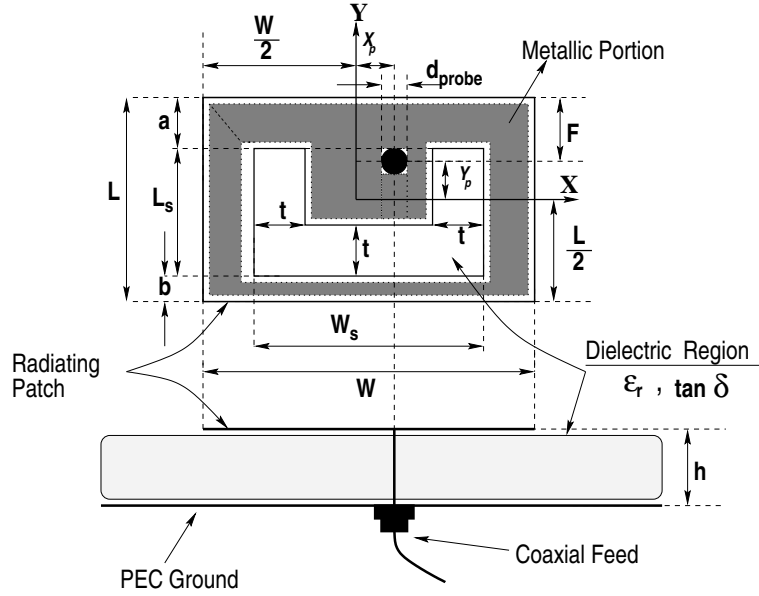


Figure 1: Physical topology of a coaxially-fed, single-layer, rectangular patch U-slot microstrip antenna.

discussed in section III. The summary is presented in section IV, followed by the list of relevant references.

II. PROCEDURE

The basic geometry of the U-slot antenna is shown in Fig. 1. For the proposed simulation study, the initial U-slot antenna topologies were initially designed on low ($\epsilon_r = 2.2$), medium ($\epsilon_r = 4.5$) and high ($\epsilon_r = 9.8$) permittivity substrates. These geometries were then optimized using parametric simulations results presented in [4] to produce wideband impedance characteristics (2:1 VSWR > 20%). The dimensions of the optimized U-slot antennas on low, medium and high permittivity substrates are shown in Table 1. The substrate thicknesses of these U-slot antennas were then varied and the corresponding effects on impedance bandwidth, radiation efficiency and gain were documented by simulation via IE3D. For each of these simulations, the term $\frac{h\sqrt{\epsilon_r}}{\lambda}$ was also calculated. Here, λ corresponds to the center frequency in the 2:1 VSWR region. It should be noted that, only substrate thickness of the U-slot antennas was varied and the topologies not optimized further to improve their bandwidth characteristics.

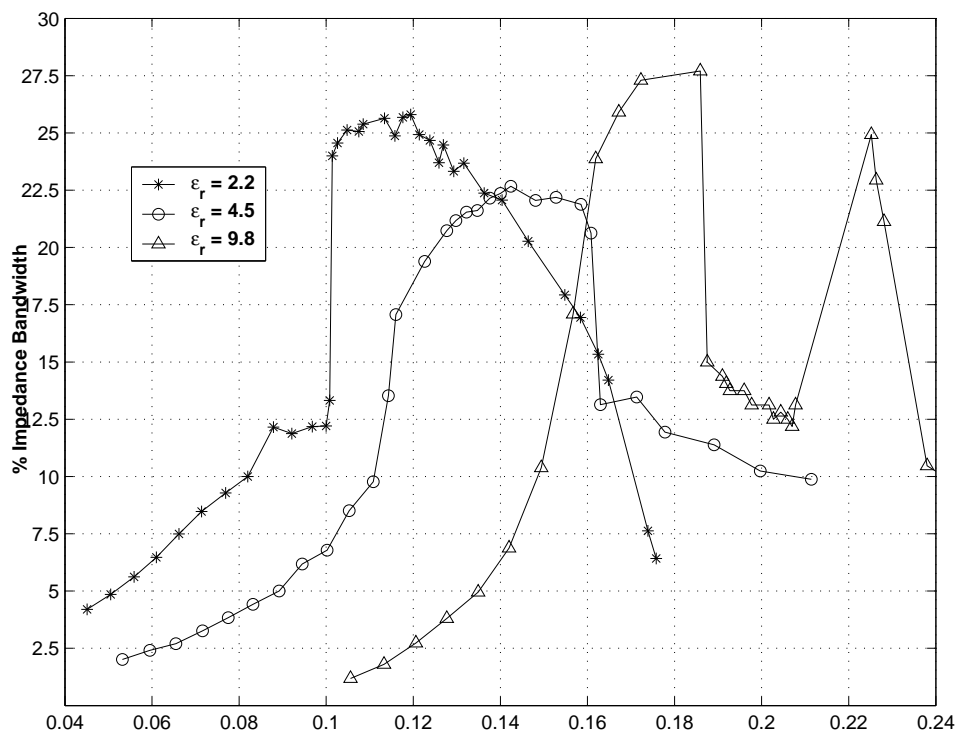
For cases of discontinuous bandwidth (or multi-band bandwidth) behavior, *only* the largest bandwidth was documented. In all these simulations, the range of substrate thickness was restricted to those values for which at least some impedance bandwidth (VSWR ≤ 2) was obtained. The result of the simulation study is presented in the next section.

III. RESULTS AND DISCUSSION

The effect of variation of substrate permittivity and thickness on impedance bandwidth for U-slot antennas are shown in Fig. 2. As seen from the figure, the impedance bandwidth of the U-slot antennas on $\epsilon_r = 2.2$ and 4.5, seem to increase rapidly with the increase in substrate thickness, reaching a plane of near-constant value and then decreasing rapidly for further increase in substrate thickness. Maximum

Parameter	Low Permittivity ($\epsilon_r = 2.2$)	Medium Permittivity ($\epsilon_r = 4.5$)	High Permittivity ($\epsilon_r = 9.8$)
$\tan(\delta)$	0.0009	0.0009	0.0009
L	47.33	35.38	26.346
W	51.15	48.9	36.45
L_s	28.61	24.5	18.24
W_s	22.23	19	14.17
t	3.2	2.74	2.04
a	6.36	7.77	4.053
b	6.36	3.11	4.053
F	18.665	15.69	6.673
R_{probe}	0.635	0.635	0.635

Table 1: Dimensions (in mm) of optimized U-slot antennas, referring to Fig. 1.

Figure 2: Variation of % impedance bandwidth versus $\frac{h\sqrt{\epsilon_r}}{\lambda}$ for probe-fed, U-slot microstrip antennas on microwave substrates. The dimensions of the U-slot antennas are tabulated in Table I.

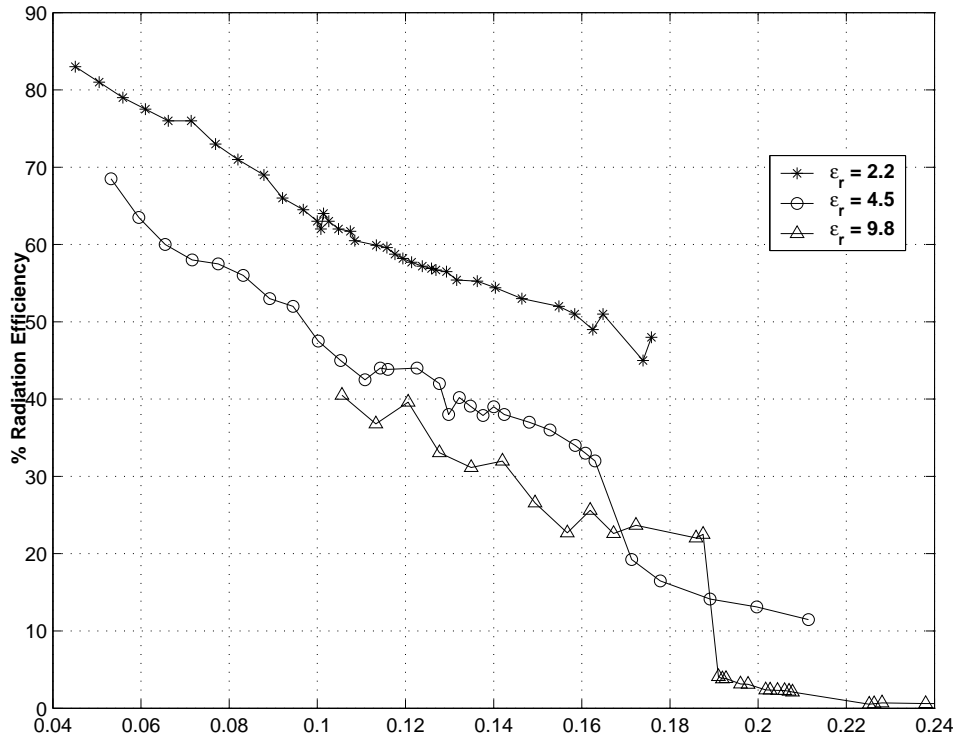


Figure 3: Variation of % radiation efficiency versus $\frac{h\sqrt{\epsilon_r}}{\lambda}$ for probe-fed, U-slot microstrip antennas on microwave substrates. The dimensions of the U-slot antennas are tabulated in Table I.

impedance bandwidths of about 26% and 23% are observed for U-slot antennas on $\epsilon_r = 2.2$ and 4.5 at $\frac{h\sqrt{\epsilon_r}}{\lambda} \approx 0.12$ and 0.14, respectively.

For U-slot antennas on $\epsilon_r = 9.8$, the impedance bandwidth curve seems to increase with the increase in substrate thickness and reach a maximum value around $\frac{h\sqrt{\epsilon_r}}{\lambda} \approx 0.185$. The impedance bandwidth drops rapidly with further increase in thickness and increases again. This behavior is interesting and needs to be investigated in greater detail. The rapid increase in the impedance bandwidth for the second time is attributed to the excitation of higher modes in the U-slot antenna.

Fig.3 shows the effects of variation of substrate thickness on radiation efficiency of U-slot antennas on low, medium and high permittivity substrates. As seen from the figure, the radiation efficiency seems to decrease with the increase in substrate thickness for U-slot on low ($\epsilon_r = 2.2$) permittivity substrate. The radiation efficiencies of U-slot antennas on $\epsilon_r = 4.5$ and 9.8 appear to exhibit damped oscillatory behavior and deteriorate rapidly after $\frac{h\sqrt{\epsilon_r}}{\lambda} \approx 0.16$ and 0.185, respectively. This rapid deterioration of radiation efficiencies of U-slot antennas on electrically thick substrates is attributed to excitation of higher order modes. The effects of substrate permittivity and thickness on gain characteristics for U-slot antennas are shown in Fig. 4. A comparison of Figs. 3 and 4 reveals that the gain characteristics follow the variation of radiation efficiency closely.

Based on the results presented in Figs. 2-4, it appears that the U-slot antennas on lower substrate permittivity exhibit superior performance compared to the U-slot antennas on higher permittivity substrates. The rapid deterioration in the radiation efficiency (and gain) in U-slot antenna geometries on

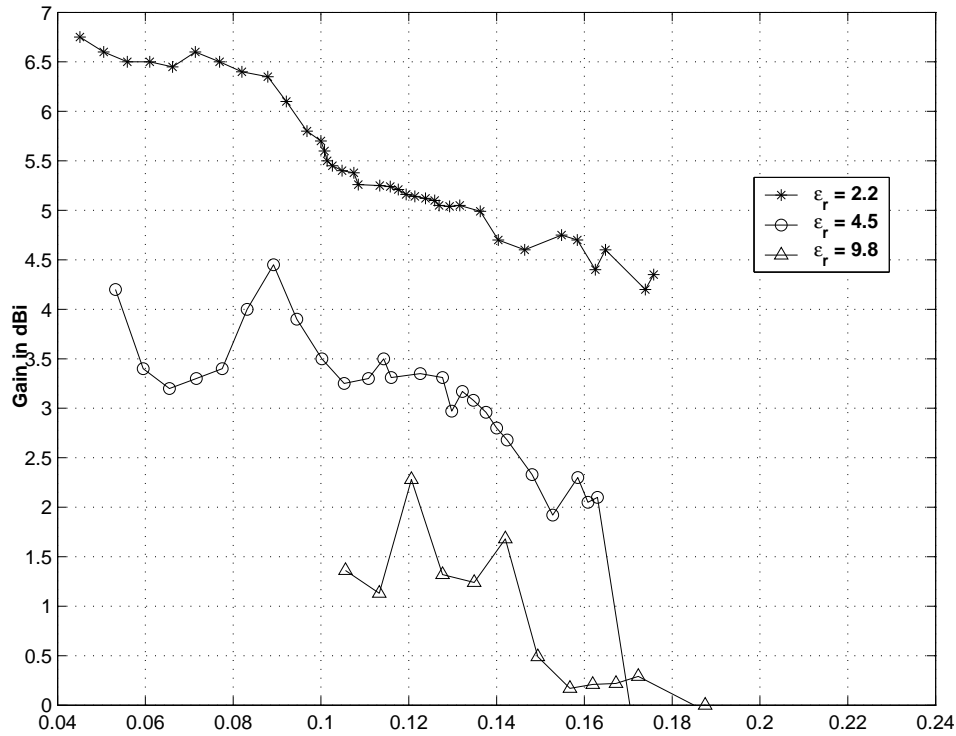


Figure 4: Variation of boresight gain($\theta = 0^\circ$, $\phi = 0^\circ$) Versus $\frac{h\sqrt{\epsilon_r}}{\lambda}$ for probe-fed, U-slot microstrip antennas on microwave substrates. The dimensions of the U-slot antennas are tabulated in Table I.

high substrate permittivities may be due to high surface wave excitations. A similar trend have been reported for square microstrip antenna in [8].

As mentioned earlier, the two different empirical techniques presented in [5] and [6] require substrate permittivity, thickness and frequency of operation as inputs to initiate the design of U-slot antennas on microwave substrates. Therefore, the information presented in Figs. 2 - 4 may be used in the selection of substrate permittivity or thickness to drastically reduce the number of optimization cycles required to obtain wideband impedance characteristics from the initial U-slot antenna geometries obtained from the empirical techniques. The applicability of these results to enable design of U-slot antennas, which can be rapidly optimized for wideband impedance characteristics are shown in [5, section VII], [10] and are omitted here fore brevity. The applicability of these results to initiate U-slot antennas on intermediate substrate permittivities is not presented here. These and other results will be presented at the time of the conference.

IV. SUMMARY

This paper investigated the effects of substrate permittivity and thickness on the performance characteristics of U-slot antennas on infinite grounded dielectrics using CAD tool IE3D. It is clearly observed that the performance of the U-slot antenna rapidly deteriorates with increase in substrate permittivity. Best impedance bandwidth results can be obtained by selection of the term $\frac{h\sqrt{\epsilon_r}}{\lambda} \approx 0.12$, 0.14 and 0.185 for U-slot antennas on $\epsilon_r = 2.2$, 4.5 and 9.8. Since, substrate permittivity, thickness and frequency are input parameters to both the empirical techniques in [5] and [6], the results of this investigation can be

used to obtain U-slot antennas which are inherently wideband, thus drastically reducing the number of optimization cycles.

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